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TECHNICAL MEMORANDUM

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IGNITION OF HYDROGEN-OXYGEN ROCKET ENGINES WITH FLUORINE

By David M. Straight and Edward A. Rothenberg

Lewis Research Center
Cleveland, Ohio

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON

December 1959

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TECHNICAL MEMORANDUM X-101

IGNITION OF HYDROGEN-OXYGEN ROCKET ENGINES WITH FLUORINE*

By David M. Straight and Edward A. Rothenberg

SUMMARY

Ignition with gaseous fluorine resulted in desirable smooth starting transients for hydrogen-oxygen rocket engines in all of 80 tests. The tests included variation of terminal chamber pressure at the end of the start transients from 90 to 320 pounds per square inch absolute and thrust from 4,000 to 24,000 pounds. A total of seven different injector - thrust chamber configurations were used.

Fluorine flow rates as low as 0.09 pound per second were injected directly into the thrust chamber through a single port and as low as 0.25 pound per second were injected into the oxygen manifold. Although minimum quantity ignition limits were not established, the total quantity of fluorine injected per start was as low as 0.15 pound through the single port and 0.5 pound in the oxygen manifold. Ignition took place with full liquid- or gaseous-hydrogen flow into the engine. Oxygen-flow-rate buildup time was varied from a 0.34-second minimum.

INTRODUCTION

The liquid-hydrogen - liquid-oxygen propellant combination is of interest for rocket systems because of the very high specific impulse obtainable. This combination is not spontaneously ignitable; therefore, a reliable, efficient ignition system is of great importance to its application.

One possible ignition source would be injection of a chemical that would ignite spontaneously with either the hydrogen or the oxygen. In addition to furnishing a large amount of ignition energy (ref. 1), the reaction could provide a continuous source of energy during the starting transient and provide restart capability. A chemical start system also offers the advantage of a simple system without the problem of safely ejecting mechanical parts from the combustion chamber after ignition as with pyrotechnic ignitors.

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Ignitor chemicals have been used in several ways with several propellant combinations. A small quantity of the chemical can be inserted in one of the main propellant flow lines which, upon starting the engine, flows ahead of the main propellant into the thrust chamber (ref. 2). Mixing of a third chemical in one of the main propellants to create a spontaneously inflammable combination when mixed with the other propellant has been used to start the oxygen - JP-4 fuel combination successfully (ref. 3). A catalytic effect of small quantities of an ignitor chemical inserted in a flow line is reported in references 4 and 5. Another method consists of a separate feed system for injecting the ignitor chemical into the thrust chamber or propellant feed line near the chamber (refs. 6 and 7).

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For the ignition of the hydrogen and oxygen propellant combination, an ignitor chemical such as fluorine or chlorine trifluoride may be chosen for spontaneous ignition with hydrogen. Pyroforic materials (spontaneously inflammable in air) such as the alkyl aluminum and alkyl boron compounds (triethyl aluminum, trimethyl boron, etc.) may be useful for spontaneous ignition with oxygen.

An ignitor chemical spontaneously flammable with hydrogen rather than oxygen was chosen for this investigation because the desired starting sequence called for a hydrogen lead to assure regenerative coolant flow in the thrust chamber at the start of combustion. Fluorine was used because of the high reactivity with hydrogen and low freezing point. The gaseous state was chosen because fluorine gas is easier to handle than liquid, particularly for the small quantities required.

The investigation included starting uncooled and regeneratively cooled engines at sea-level conditions. Terminal thrust levels were from 4,000 to 24,000 pounds at chamber pressures from 90 to 320 pounds per square inch absolute. Several fluorine flow rates and injection methods were used. A few runs were made in which oxygen-flow-rate buildup time was varied.

The data were analyzed to determine ignition characteristics and smoothness of transition to full thrust. Experimental conditions are presented in tabular form. Time records showing variation of flow rates and chamber pressure for a typical starting transient are also presented.

APPARATUS

The tests were made in the Rocket-Engine Research Facility of the Lewis Research Center. A general description of the facility is presented in reference 8.

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Propellant Systems

Figure 1 shows the arrangement of the propellant systems in the test building. The liquid oxygen was supplied to the engine from the oxidant pit through the same system described in reference 8. The vacuum-jacketed liquid-hydrogen propellant tank was located outside the test building shown in figure 1. The liquid was pressurized with gaseous hydrogen and flowed to the engine through stainless-steel piping and valves. The flow line and valves were covered with 6 inches of foamed glass insulation along the 40-foot length from the tank to the engine.

The gaseous fluorine was stored in a 10-cubic-foot stainless-steel tank located between the fuel and oxidant pits. Stainless-steel piping and valves were used to bring the fluorine into the test cell and to the engine.

Propellants

Oxygen of 99.5 percent purity was stored and used as a liquid in facility containers.

Both gaseous and liquid hydrogen were used in the investigation. Gaseous hydrogen was received in high-pressure tube trailers and pumped into the facility storage manifold where ambient-temperature storage conditions exist. Liquid hydrogen was received with a minimum concentration of 96 percent parahydrogen and was transferred into the facility liquid-hydrogen tank.

The fluorine gas used throughout the tests was produced by vaporizing liquid fluorine stored in facility containers. Purity was about 99 percent.

Flow Control

Both propellant flow rates were controlled through hydraulically actuated throttling globe-valves. The open position of the valve plug was preset to produce the desired flow rates. Propellant tank pressure was held constant. The rate of valve travel from closed to preset open position was adjustable from a few milliseconds to 2 seconds. The flow system, however, limited the minimum flow buildup time of the oxygen to about 0.3 second.

Fluorine flow rates varied with the pressure (400 to 700 lb/sq in.) in the supply tank and the flow resistance of the feed line between the tank and the engine. The fluorine fire valve (fig. 1) was a pneumatically actuated valve with an adjustable stop on the open position.

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Flow Measurement

Oxygen flow was measured with a Venturi flowmeter which was calibrated with liquid oxygen. The meter as well as the tank and lines leading to the meter was immersed in liquid nitrogen to maintain the oxygen at a uniform temperature. Gaseous-hydrogen flow was metered through a flat-plate orifice machined to ASME specifications. A Venturi meter was used to measure liquid-hydrogen flow. In order to minimize temperature and pressure variations at the flowmeter, the meter was located in the propellant tank dip tube, which carried the liquid out of the tank. The meter was calibrated with air, under pressure, at Reynolds numbers equivalent to those of the flowing liquid hydrogen. The fluorine flow was measured with a standard ASME orifice plate. The probable error in flow measurements at steady flow conditions, including density determinations, was less than 1.5 percent, except for fluorine flow where the probable error was within 10 percent. Although these accuracies apply for steady-state flow conditions, the accuracy is more uncertain during flow transients, particularly when flow line fill times are appreciable. The hydrogen and fluorine flow data reported herein are probably within these accuracies since flow rates were stabilized at ignition. Oxygen flow, however, is subject to error because of the fill time of the oxygen line between the fire valve and the engine.

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Pressure Measurement

Chamber pressure and propellant flowmeter pressures and pressure drops were measured with strain-gage-type pressure transducers. The output of each transducer was recorded on both a self-balancing potentiometer and a direct-reading oscillograph. The probable error of the pressure measurements, as recorded on the potentiometers, was no greater than 0.75 percent at steady operating conditions.

The ability of the pressure transducers and associated instrumentation to indicate sudden large changes in pressure is illustrated by the pressure-time curves presented in figure 2. Insufficient voltage supply to a pyrotechnic ignitor caused an ignition delay of about 0.9 second after oxygen flow started. The resulting pressure spike shown in figure 2 indicates that the instrumentation used for the chamber pressure measurement was capable of responding to a sudden pressure change that occurred in less than 0.002 second. The pressure level, however, indicated by such spikes is not accurate because of the dynamics of the tube connecting the pressure transducer to the thrust chamber.

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Thrust Measurement

Thrust was measured with strain-gage load cells. Three cells were used to measure the total engine thrust. The outputs of the transducers were summed electrically and recorded on a self-balancing potentiometer. Calibrations indicated a probable error of 0.6 percent.

ENGINE CONFIGURATIONS

Thrust Chambers

The three thrust chamber configurations used in the investigation are presented in figure 3. The uncooled chambers (figs. 3(a) and (b)) were used for the early exploratory runs. Later runs were made with regeneratively cooled thrust chambers (fig. 3(c)).

The uncooled chambers were constructed of carbon steel, 1/2 inch thick except for the heavier throat section. The inner surface was coated with an aluminum oxide refractory. The regeneratively cooled chambers were constructed of thin stainless steel or nickel channels with outside wire wrapping for strength.

The contraction ratio for all three chambers was 1.9. The long uncooled chamber (fig. 3(a)) and the regeneratively cooled chamber (fig. 3(c)) were both designed for a nominal 20,000-pound thrust with sea-level expansion at a chamber pressure of 300 pounds per square inch absolute. The expansion area ratio was 3.68. The short uncooled engine was designed for a nominal 9000-pound thrust with sea-level expansion at a chamber pressure of 150 pounds per square inch absolute. The expansion area ratio for this engine was 2.39.

Injectors

Drawings of the injectors used in the investigation are presented in figures 4 and 5. The basic construction of the injectors and the method of cooling the injector face are shown in figure 4. Oxygen from the oxygen manifold flows through many individual tubes directly into the combustion chamber. A hydrogen manifold is located at the periphery of the injector (fig. 6). This manifold is supplied with hydrogen directly from the supply source when uncooled chambers are used. The coolant passages of the regeneratively cooled engines feed hydrogen directly into the injector. Hydrogen flows radially inward between the oxygen tubes from the periphery of the injector and is distributed to injector face coolant passages by many holes in a back face coolant distribution plate. The hydrogen passes through the coolant passages at high velocity and then through the injection orifices into the combustion chamber.

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Figure 5 presents the propellant injection patterns used. These included straight showerhead pattern for both oxygen and hydrogen (figs. 5(a) and (c)), converging showerhead for oxygen only (fig. 5(b)), converging showerhead for both oxygen and hydrogen (fig. 5(e)), and a like-on-like oxygen impingement with showerhead hydrogen (fig. 5(d)). Three degrees of pattern fineness (oxygen tube spacing) were used (figs. 5(a), (c), and (e)). The fuel and oxidant holes were uniformly and symmetrically spaced except around the periphery; only fuel was injected through the outermost holes.

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The injector face and oxygen tubes of injectors A, B, and D (figs. 5(a), (b), and (d)) were fabricated from copper, whereas the oxygen distribution plate was stainless steel. All parts of injector C (fig. 5(c)) were made from aluminum. Injector E (fig. 5(e)) was made from nickel with a stainless-steel oxygen distribution plate.

Fluorine Injection Methods

Three methods of injecting fluorine into the combustion chamber were used as shown in figure 6.

The first method consisted of inserting a 5/16-inch stainless-steel tube through a hole in the center of the injector and brazing it into place with the end of the tube flush with the face of the injector (fig. 6(a)). One oxygen jet was eliminated with this method; however, the four hydrogen jets surrounding it remained. A local reaction between the hydrogen flowing through these four jets and the fluorine flowing through the tube becomes the ignition source for the chamber. When injectors C and E were used, the fluorine tube was mounted to inject fluorine through the side of the uncooled engines (fig. 6(b)). The fluorine, in this case, reacts with hydrogen flowing perpendicular to it. When the regeneratively cooled engines (fig. 3(c)) were used, the fluorine was injected into the oxygen manifold as shown in figure 6(c). The fluorine then flows through the oxygen tubes into the combustion chamber. With this method, the injected fluorine is diluted by helium purge gas flowing through the injector during the start transient and is probably spread out considerably over the area of the injector. Prior to starting the engine by this method, the injector and oxygen manifold were thoroughly cleaned for fluorine service.

PROCEDURE AND TEST CONDITIONS

Engine starting was controlled by an electrical sequence timer. All firings were made with basically the same starting sequence by using a hydrogen lead to establish full operating flow at ignition. With liquid hydrogen, this lead time was set as long as 4.5 seconds to cool the flow

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line and engine before starting oxygen flow. Fluorine was injected about 1 second before the start of oxygen flow. The pressure drop across the fluorine flow orifice was used as a permissive signal to be sure the ignition source was present before oxygen was allowed to flow into the chamber. The sequence timer was used to shut off the fluorine fire valve at a preset time after the oxygen fire valve was opened.

The sequence timer was set to allow at least 0.5 second of operation at full thrust to ensure that the complete start was recorded. The data presented herein include, however, all starts obtained even though full thrust was not attained because of shutdown caused by automatic facility operation monitoring systems such as low or high thrust, propellant flows, chamber pressure, and so forth.

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A summary of the test conditions and engine configurations used is presented in the following table:

Fluorine injection method	Injector face	Side injection	Oxygen manifold
Thrust chambers (fig. 3)	Long uncooled	Long uncooled Short uncooled	Long uncooled Short uncooled Regeneratively cooled
Injectors (fig. 5)	A, B, D	C, E	B, C, E
Hydrogen state	Liquid and gaseous	Gaseous	Liquid
Chamber pressure, lb/sq in.	150 and 300	150 and 300	100 to 300
Nominal thrust, lb	9,000 and 20,000	9,000 and 20,000	6,000 to 20,000
Mixture ratio, percent fuel	10 to 24	10 to 24	10 to 24

Fluorine flow rates were varied over a range of approximately 0.1 to 0.5 pound per second. No attempt was made to establish a minimum fluorine flow rate or minimum injection time below which ignition would not occur. Oxygen-flow-rate-buildup time was varied from approximately 2.0 seconds down to the minimum obtainable of about 0.3 second.

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RESULTS AND DISCUSSION

A total of 80 test runs were made using gaseous fluorine for igniting hydrogen-oxygen rocket engines over the wide range of configurations and operating test conditions summarized in the preceding section.

Desirable smooth ignition and thrust buildup were obtained for all 80 runs independent of operating conditions and engine configuration. No chamber pressure spikes occurred in any run. Data records with a common time reference showing one typical start transient are presented in figure 7. The curves are recorded pressure drop - time data from the flowmeters used for hydrogen, oxygen, and fluorine. The flows indicated in parentheses are approximate values from the orifice calibration curves.

Full hydrogen flow is first established and is followed by fluorine injection which ignites spontaneously with the hydrogen. Oxygen is then fed into the chamber. Chamber pressure buildup occurs smoothly as oxygen flow increases to the desired full flow operating conditions. The overshoot at the beginning of the fluorine flow trace is caused by the flow through the orifice during the fill time of the system downstream of the fluorine fire valve. The fluorine flow into the chamber is reduced by the rising chamber pressure during the starting transient and is then shut off by the sequence timer. The apparent oscillations in the traces at the start of the oxygen flow and during the steady flow of hydrogen, oxygen, and fluorine are normal perturbations of pressure in the propellant flow systems.

The data obtained covered a range of chamber pressure of approximately 90 to 320 pounds per square inch absolute, thrust of 4,000 to 24,000 pounds, and fuel flow rate of 7 to 47 percent of total propellant flow. These were the conditions at the end of the starting transient and include runs with incomplete ramps. Detailed information on engine configuration, flow programing, conditions at ignition and at the end of the oxygen flow ramp for each of the 80 runs are presented in table I and in the following paragraphs. The values given in table I for conditions at the end of the oxygen ramp are approximate and should not be used for performance calculations since a few additional tenths of a second are usually required for complete equilibrium of conditions.

Fluorine Injection Method

The first ignition attempts were made with the fluorine tube brazed into the face of the injector (fig. 6(a)). Oxygen-flow-rate buildup time was set very long for these runs (runs 1 to 5, table I) in order to test feasibility of ignition with the fluorine. It was found that decreasing the time of oxygen-flow-rate buildup to the minimum obtainable had no

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effect on smoothness of the start transient. A total of 11 runs were made with this injection method using fluorine flow rates from 0.17 to 0.30 pound per second.

In runs 12 to 21 (table I), fluorine was injected through the side of the engine (fig. 6(b)). Even though fluorine flow rates were as low as 0.09 pound per second for some runs, ignition and transition to full thrust were equally satisfactory. A total of 10 runs were made with side injection of fluorine.

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Injection of fluorine through the tube for both injector face or side injection resulted in some burning of the end of the injection tube. More adequate cooling of the tube would probably overcome this difficulty.

Initial tests with fluorine injection into the oxygen manifold (fig. 6(c)) were made with the aluminum injector C (fig. 5(c)) and an uncooled thrust chamber (fig. 3(a)). In runs 22 to 31 oxygen-flow-rate buildup times were again varied from 1.72 to 0.35 second to determine if the spreading and dilution of the fluorine with helium purge gas or oxygen during the start transient would cause difficulty. No difficulty was encountered in these or the subsequent runs.

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A total of 59 successful starts was made with fluorine injection into the oxygen manifold; 34 of these were with regeneratively cooled engines and the lightweight injector E (fig. 5(e)). Fluorine flow rates used varied from 0.52 to as low as 0.25 pound per second. Inspection of one of these injectors after 22 starts indicated only a light fluoride coating on all exposed surfaces. Photographs of the injector are presented in figure 8.

Quantity of Fluorine

The total quantity of fluorine required per start is of interest to minimize the weight of an ignition system. The smallest amount used for a single start in this investigation was approximately 0.15 pound using side injection. Since no attempt was made to find an ignition limit, lower flow rates or shorter injection times and thus smaller quantities of fluorine may be possible. The smallest quantity injected into the oxygen manifold was about 0.5 pound.

Flame Propagation Mechanism

When the fluorine was injected through a tube brazed into the face of the injector where it was surrounded by four hydrogen jets, a hot local torch of burning hydrogen and fluorine probably occurred in the center of the combustion chamber. When oxygen entered the chamber, the

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flame probably spread radially to fill the chamber and continued burning smoothly as oxygen flow increased until full thrust was attained.

With side injection of fluorine, the local flame was probably spread over a greater volume of the combustion chamber. Even though the fluorine flow was as low as 0.09 pound per second for some starts, no loss in effectiveness was evident.

When fluorine is injected into the oxygen manifold, it is diluted somewhat by helium purge gas and then spreads and flows through many of the oxygen tubes into the combustion chamber. The local concentration of fluorine is probably much lower than for single-port injection even though higher total flow was used. Since hydrogen is at full flow conditions when fluorine arrives in the chamber, it is probable that the fluorine reacts with only small quantities of hydrogen at the fringes of the hydrogen jets. When oxygen flow commences, it displaces the fluorine flowing through the injection orifices, and flame in recirculation regions between injection orifices propagates throughout the hydrogen-oxygen mixture.

Although no evidence of ignition delay was observed in all runs, it is possible that there may be a minimum oxygen-flow-rate buildup time below which difficulty may be encountered with fluorine injection in the oxygen manifold.

The ignition mechanism for all starts reported herein is probably that of point ignition where hydrogen and fluorine mix, followed by flame propagation from these small local high-temperature regions to the overall hydrogen-oxygen mixture. If it were assumed that all the injected fluorine reacted with hydrogen and that the heat released was absorbed by all the hydrogen entering the chamber, the resulting temperature would not be high enough to ignite the hydrogen with the oxygen when it arrived in the chamber. The ignition temperature of hydrogen and oxygen mixtures is of the order of 1200° F (refs. 9 to 11).

Possibilities of Other Ignitor Chemicals

Gaseous fluorine has been shown herein to be an excellent ignition source for starting hydrogen-oxygen engines. Use of liquid fluorine or other liquid ignitor chemicals (chlorine trifluoride, trimethyl boron, etc.) may have practical advantages from weight and volume considerations for use in flight systems. Further investigation is required to establish feasibility of these liquid chemicals. Information is required on their effectiveness as ignition sources, flow rates, and flow sequencing during the start transient. The higher freezing points of some of these chemicals and storage and handling of small quantities of liquid fluorine may present problems.

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SUMMARY OF RESULTS

Results obtained from igniting hydrogen-oxygen rocket engines with gaseous fluorine are summarized in the following paragraphs. Thrust level was from 4,000 to 24,000 pounds at chamber pressures from 90 to 320 pounds per square inch absolute. Experiments were made with both liquid and warm gaseous hydrogen and liquid oxygen. Seven different thrust chamber - injector configurations were used.

1. Smooth ignition and thrust buildup were obtained in all of 80 start attempts.

2. Ignition was successful with the fluorine injected either through the side of the engine, through a tube inserted into the face of the injector, or into the oxygen manifold of the engine.

3. The minimum fluorine flow rates used were 0.09 pound per second into the combustion chamber and 0.25 pound per second for oxygen manifold injection. The minimum total quantities injected per start were 0.15 and 0.5 pound, respectively.

4. Ignition with gaseous-fluorine injection into the oxygen manifold showed no material compatability problems. Normal cleaning for fluorine service was performed before operation of the engine.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 13, 1959

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TABLE I. - ENGINE START DATA WITH GASEOUS-FLUORINE IGNITION

Run number	Engine configuration		Hydrogen supply state (c)	Flow programing				Fuel flow at ignition, lb/sec	Fluorine flow at ignition, lb/sec	Oxygen ramp time, sec	Oxygen flow at end of ramp, lb/sec	Fuel at end of ramp, percent	Chamber pressure at end of ramp, lb/sq in. abs	Thrust at end of oxygen ramp, lb	Remarks
	Chamber (a)	Injector (b)		Start hydrogen flow, sec	Start fluorine injection, sec	Start oxygen flow, sec	End oxygen ramp, sec								
						(a) Fluorine injection at injector face									
1	Long U.C.	B	Liquid	0	2.25	4.40	6.17	16.5	0.30	1.77	----	----	[d]300	21,550	
2					2.25	4.50	6.32	16.1	.28	1.82	51.0	24.0		20,000	
3					2.27	4.29	5.34	15.4	.27	1.05	35.8	21.6		19,250	
4					2.31	4.18	4.64	15.4	.25	.46	56.4	21.4		19,300	
5					2.25	4.03	4.53	15.1	.24	.50	57.1	21.0		19,000	
6	Long U.C.	D	Liquid	0	1.50	2.16	2.50	12.4	0.30	0.34	52.3	19.1	[d]300	23,750	
7	Long U.C.	A	Gas	0	1.42	1.96	2.76	6.46	0.23	0.80	53.7	10.8	248	17,300	
8					1.56	2.09	2.80	12.7	.17	.71	53.7	17.6	317	22,500	
9					1.71	2.34	3.05	5.55	.20	.71	20.3	21.5	121	7,550	
10					1.76	2.29	2.92	6.30	.18	.63	24.9	19.8	145	9,450	
11					1.84	2.34	3.03	6.38	.18	.69	21.1	22.8	153	10,500	
						(b) Fluorine injection through side of engine									
12	Long U.C.	C	Gas	0	0.61	1.09	2.00	8.35	0.23	0.91	56.5	12.4	286	19,200	
13					.57	.99	1.91	7.77	.22	.92	62.0	12.0	281	18,800	Incomplete ramp
14					.58	1.10	1.85	7.46	.22	.75	21.1	25.4	95	5,600	
15					.57	1.05	1.71	4.82	.21	.66	27.1	14.6	151	8,800	
16	Short U.C.	E	Gas	0	.27	1.77	1.90	7.2	0.11	0.13	22.7	24.1	155	6,380	Incomplete ramp
17					.28	1.11	1.88	5.8	.11	.77	31.3	15.6	182	11,740	
18				[e].165	0	1.86	1.98	4.42	.11	.12	29.6	13.0	160	4,660	Incomplete ramp
19				[e].165	0	1.64	1.82	4.46	.10	.18	33.8	11.7	179	10,320	Incomplete ramp
20				0	0	1.28	1.63	5.39	.10	.35	32.3	14.3	168	11,040	
21				0	.06	1.50	1.69	-----	.09	.19	31.4	----	152	9,700	Incomplete ramp
						(c) Fluorine injection in oxygen manifold									
22	Long U.C.	C	Liquid	0	1.28	2.64	4.16	15.7	0.50	1.52	59.8	20.0	285	18,410	
23					1.33	2.87	3.75	13.1	.48	.88	14.8	46.6	119	6,409	Incomplete ramp
24					1.38	2.77	4.49	15.0	.43	1.72	59.3	18.8	284	19,030	
25					1.35	2.66	3.15	16.3	.42	.49	34.2	31.6	224	10,066	Incomplete ramp
26					1.35	2.66	3.69	16.2	.40	1.03	54.5	21.8	295	18,830	
27					1.33	2.66	3.70	15.9	.38	1.04	54.9	21.3	300	20,290	
28					1.32	2.46	2.96	16.3	.36	.50	53.3	22.5	284	18,720	
29					1.38	2.56	3.02	16.5	.34	.46	52.6	22.8	284	19,110	
30					1.38	2.63	3.04	15.0	.34	.41	53.3	20.9	274	19,110	
31					1.44	2.62	2.97	15.1	.33	.35	53.3	21.2	258	17,690	
32	Short U.C.	E	Liquid	0	1.24	2.46	3.12	4.99	0.33	0.66	32.4	13.2	130	6,730	Incomplete ramp
33					1.31	2.84	3.34	4.94	.32	.50	33.2	13.0	120	6,750	Warm oxygen line
34					1.27	2.49	3.66	5.64	.32	1.17	24.9	18.2	152	8,450	Warm oxygen line
35					1.26	2.49	3.62	5.67	.31	1.13	25.8	18.2	170	9,365	Warm oxygen line
36	R.C.	E	Liquid	0	1.82	3.25	3.88	3.91	0.32	0.63	31.7	10.9	157	9,130	
37					1.83	3.29	4.00	4.07	.31	.71	31.9	11.1	174	11,020	
38					1.81	3.28	4.05	4.45	.48	.77	28.8	13.4	170	10,360	
39					2.36	3.89	4.62	3.42	.42	.73	26.5	11.4	147	9,190	
40					2.73	4.18	4.96	3.16	.40	.78	38.4	7.6	130	5,974	
41					2.66	4.14	4.81	3.45	.39	.67	38.9	8.1	141	6,686	
42					2.78	4.31	5.06	3.48	.35	.75	26.1	11.7	140	8,860	
43					2.80	4.26	5.68	3.53	.34	1.42	28.0	10.7	154	9,494	
44					2.78	4.14	5.00	3.52	.47	.86	28.0	11.0	150	9,020	
45					2.62	4.23	5.26	4.51	.47	1.03	19.5	18.5	117	6,590	
46					2.72	4.28	5.04	4.82	.47	.76	28.1	14.1	164	9,446	
47					2.68	4.12	4.89	4.99	.42	.77	34.2	12.4	191	11,300	
48					2.74	4.24	4.95	5.50	.40	.71	38.6	11.8	212	12,820	
49					2.70	4.22	4.88	3.57	.40	.66	30.1	10.5	156	9,226	
50					2.66	4.18	4.82	3.04	.34	.64	27.5	9.9	150	9,190	
51					2.84	4.26	4.92	3.67	.50	.66	32.2	9.8	162	8,920	
52					2.90	4.43	5.10	4.31	.49	.67	27.9	13.1	155	8,730	
53	Short U.C.	E	Liquid	0	1.83	3.48	4.05	1.93	0.32	0.57	26.0	7.00	113	------	
54					1.99	3.73	4.22	2.57	.31	.49	28.0	8.45	143	8,700	
55					1.96	3.65	4.24	2.59	.30	.59	31.1	7.68	157	9,860	
56	R.C.	E	Liquid	0	1.94	3.69	4.30	3.32	0.31	0.61	25.8	11.4	112	4,560	
57					1.88	3.88	4.28	3.62	.29	.40	19.2	15.5	137	6,270	
58					1.85	3.73	4.48	3.70	.28	.75	18.0	16.8	107	5,870	
59					1.83	3.50	4.28	3.43	.27	.78	20.1	14.4	117	6,530	
60					1.82	3.71	4.16	3.58	.25	.45	22.2	13.8	126	7,460	
61					1.98	3.70	4.47	4.32	.48	.77	19.4	18.4	121	6,770	
62					2.02	3.70	4.32	3.22	.39	.62	16.4	16.4	113	6,170	
63					1.97	3.78	4.45	3.75	.37	.67	----	-----	156	10,520	
64					1.96	3.78	4.44	3.82	----	.66	16.6	18.5	107	5,560	
65					2.01	3.94	5.31	3.44	.34	1.37	12.8	21.4	86	3,840	
66					1.66	3.24	4.13	14.0	----	.89	38.6	26.6	252	11,000	
67					1.69	3.24	4.16	14.0	----	.92	39.2	23.4	236	12,500	
68					1.64	3.39	4.17	10.0	.52	.79	62.0	12.5	304	21,440	
69					1.67	3.50	4.24	8.22	.39	.74	57.3	12.6	269	20,075	
70					1.64	3.45	4.19	7.60	.37	.74	61.0	11.1	290	20,075	
71					1.65	3.39	4.09	8.78	.35	.70	56.8	12.9	274	20,075	
72					1.67	3.43	4.19	9.30	.33	.76	53.0	14.2	290	21,285	
73	R.C.	B	Liquid	0	1.77	3.54	4.23	11.5	0.31	0.69	54.5	15.2	300	19,600	
74					1.47	3.24	3.97	8.64	.29	.73	52.2	13.3	306	19,800	
75					1.61	3.40	4.11	10.2	.28	.71	52.2	14.6	311	21,600	
76					1.77	3.57	4.31	-----	.26	.74	52.6	16.6	314	22,200	
77					1.65	3.40	4.16	7.68	.42	.76	62.8	10.5	290	22,150	
78					1.54	3.34	4.07	7.73	.40	.73	55.6	11.8	275	19,600	
79					1.63	3.39	4.09	10.80	.38	.70	51.1	15.8	280	19,250	
80					1.67	3.53	4.26	10.95	.37	.73	52.8	15.3	280	18,650	

[a]U.C. = Uncooled, R.C. = regeneratively cooled.
[b]See fig. 3.
[c]Liquid at approx. 40° R; gas at ambient temperature (460° to 510° R).
[d]Nominal value.
[e]Fluorine flow before hydrogen flow.

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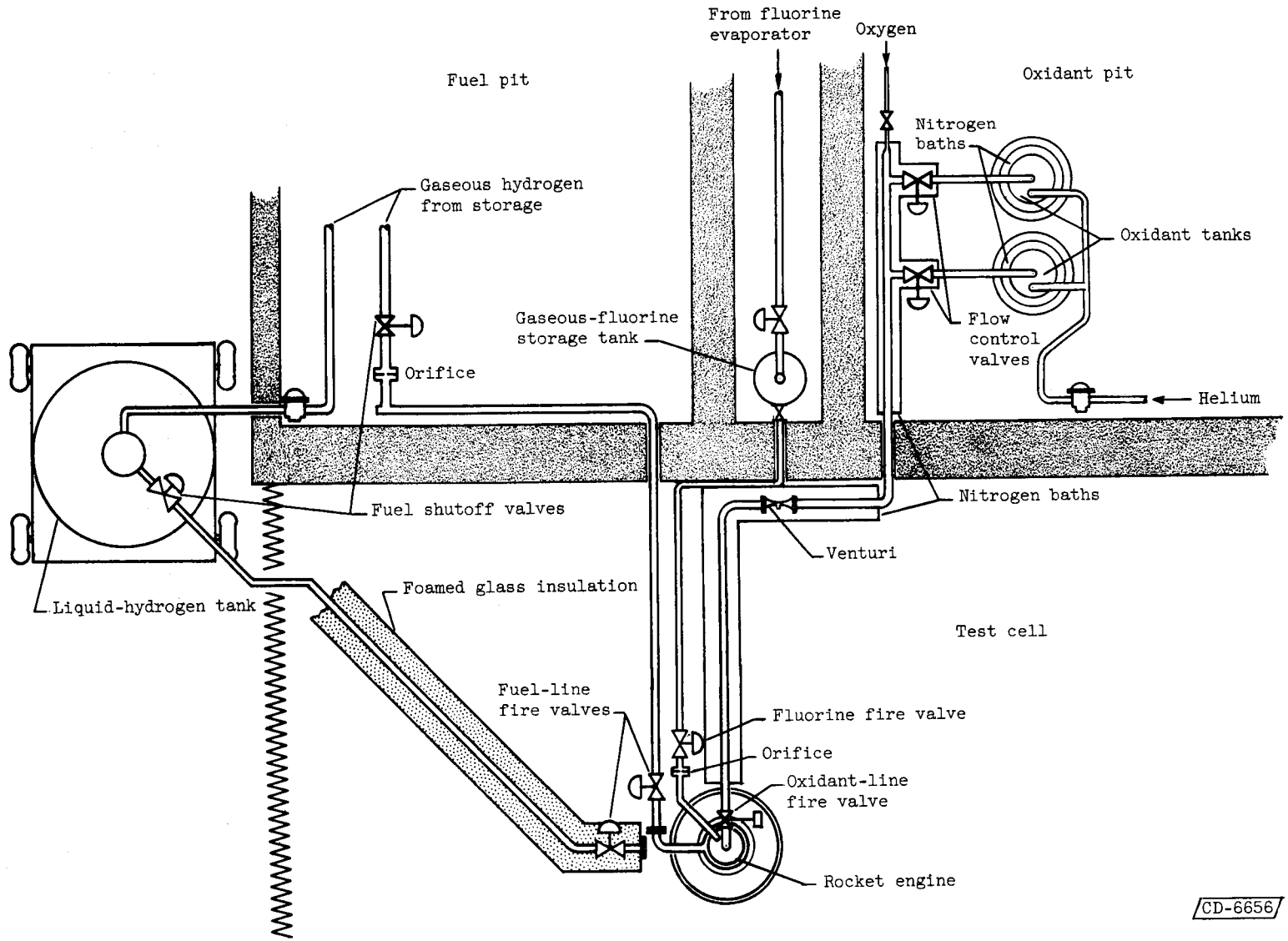

Figure 1. - Arrangement of propellant systems in test building.

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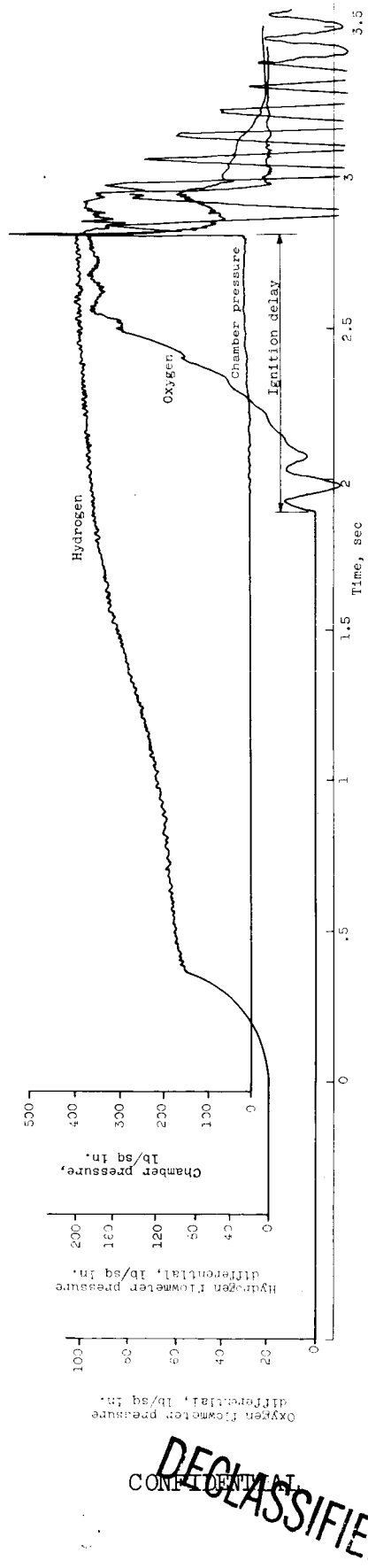

Figure 2. - Direct-reading oscillograph record of a hard start (pyrotechnic ignitor).

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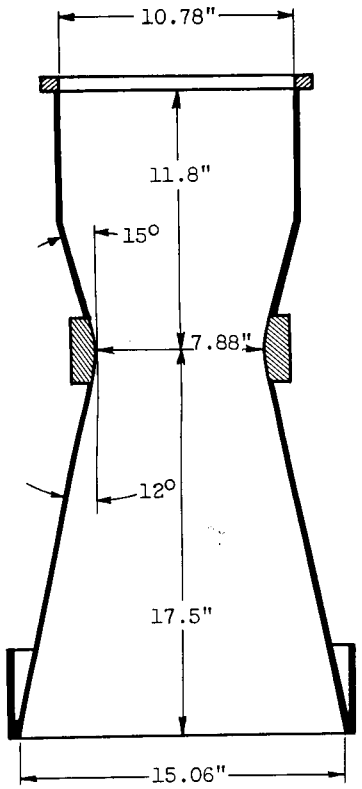
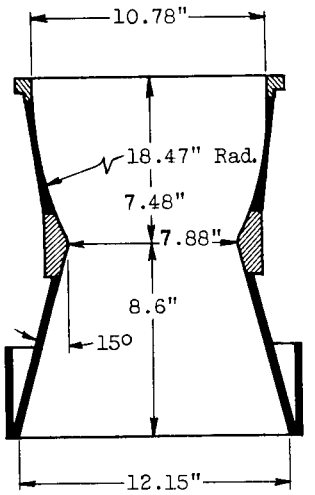
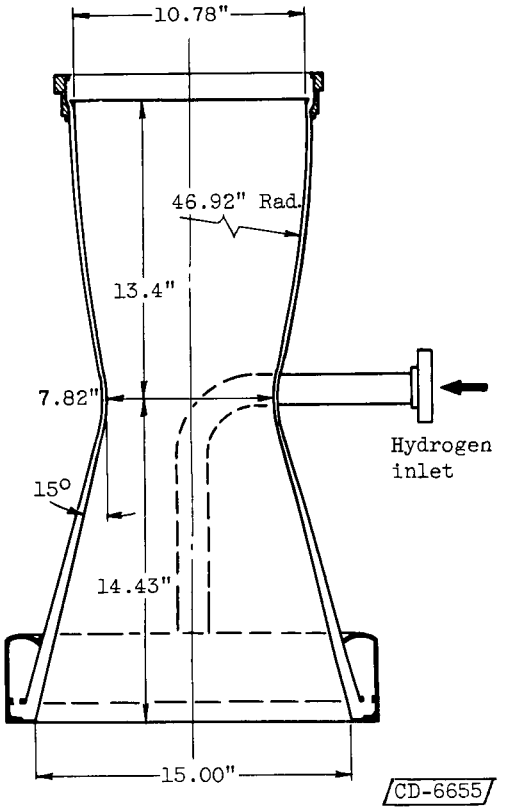


(a) Long uncooled chamber.



(b) Short uncooled chamber.



(c) Regeneratively cooled chamber.

Figure 3. - Thrust chambers used in starting investigation.

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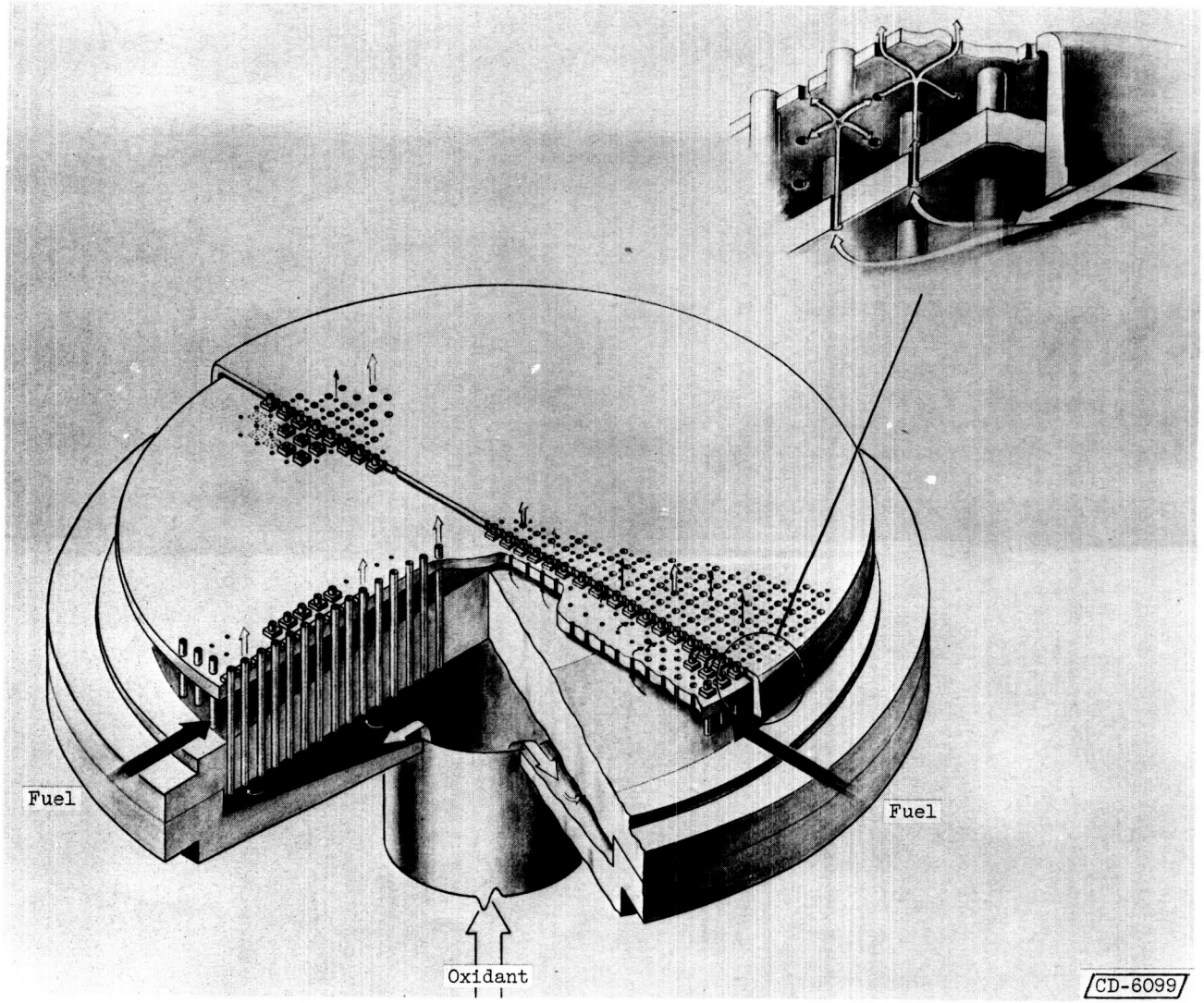

Figure 4. - Cutaway view of injector showing propellant distribution method.

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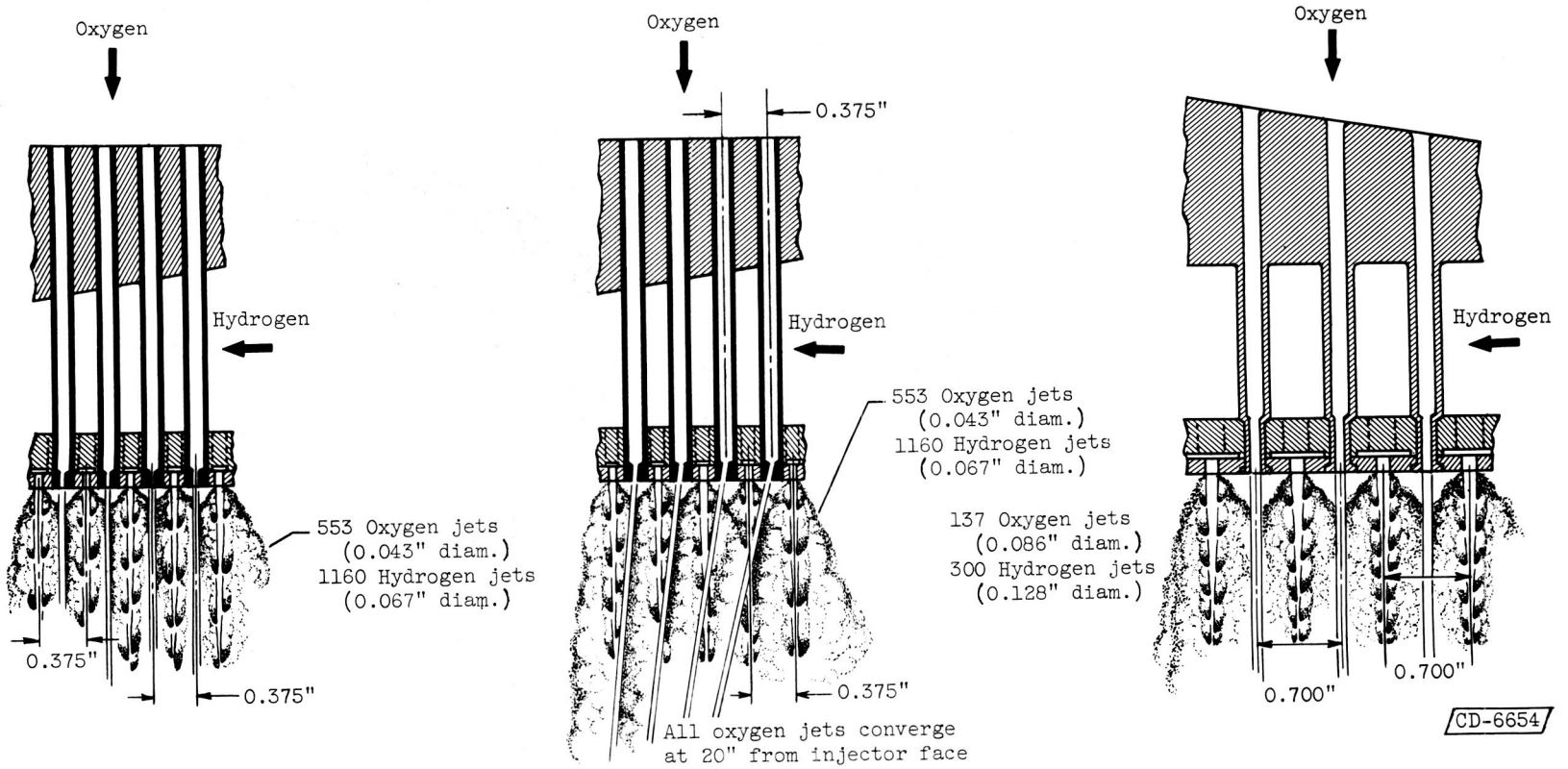

(a) Injector A.

(b) Injector B.

(c) Injector C.

Figure 5. - Injectors used in starting investigation.

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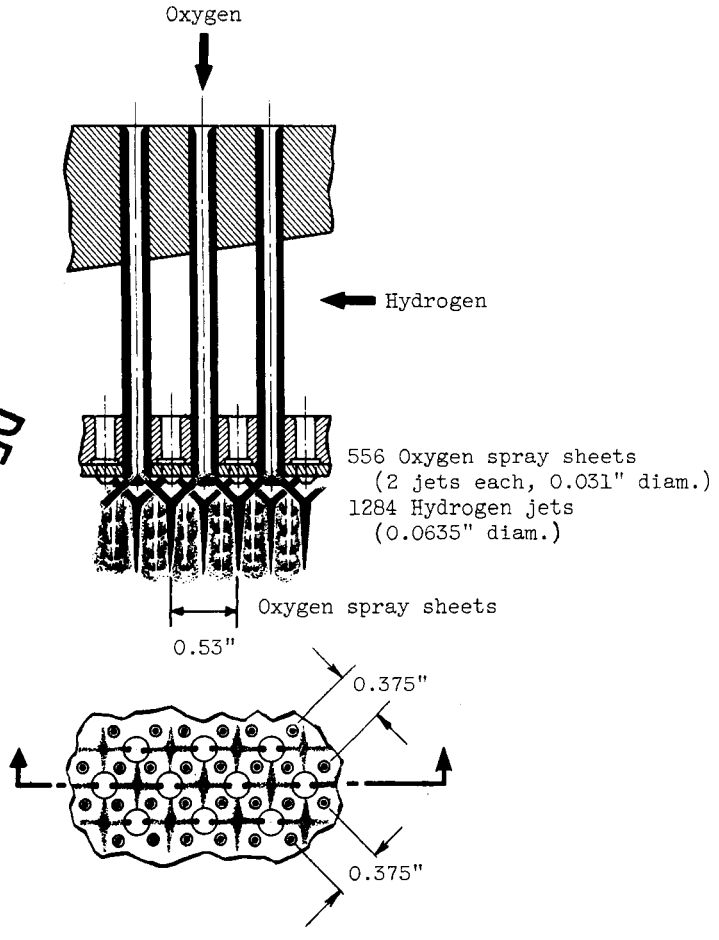
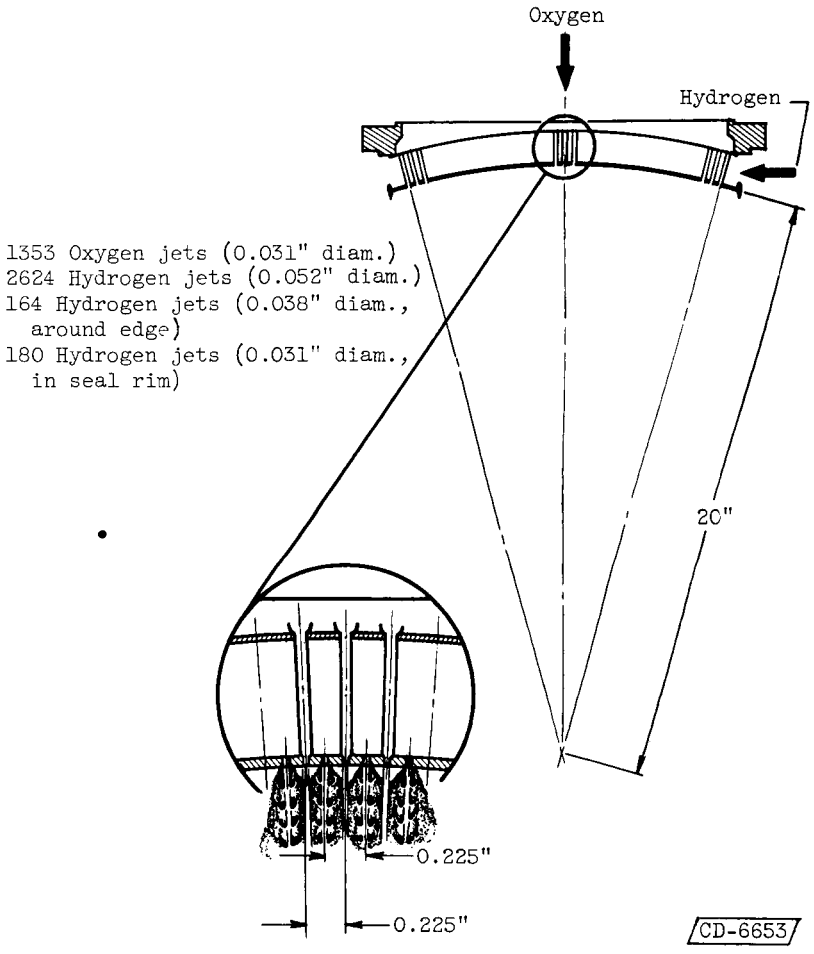


(d) Injector D.



(e) Injector E.

Figure 5. - Concluded. Injectors used in starting investigation.

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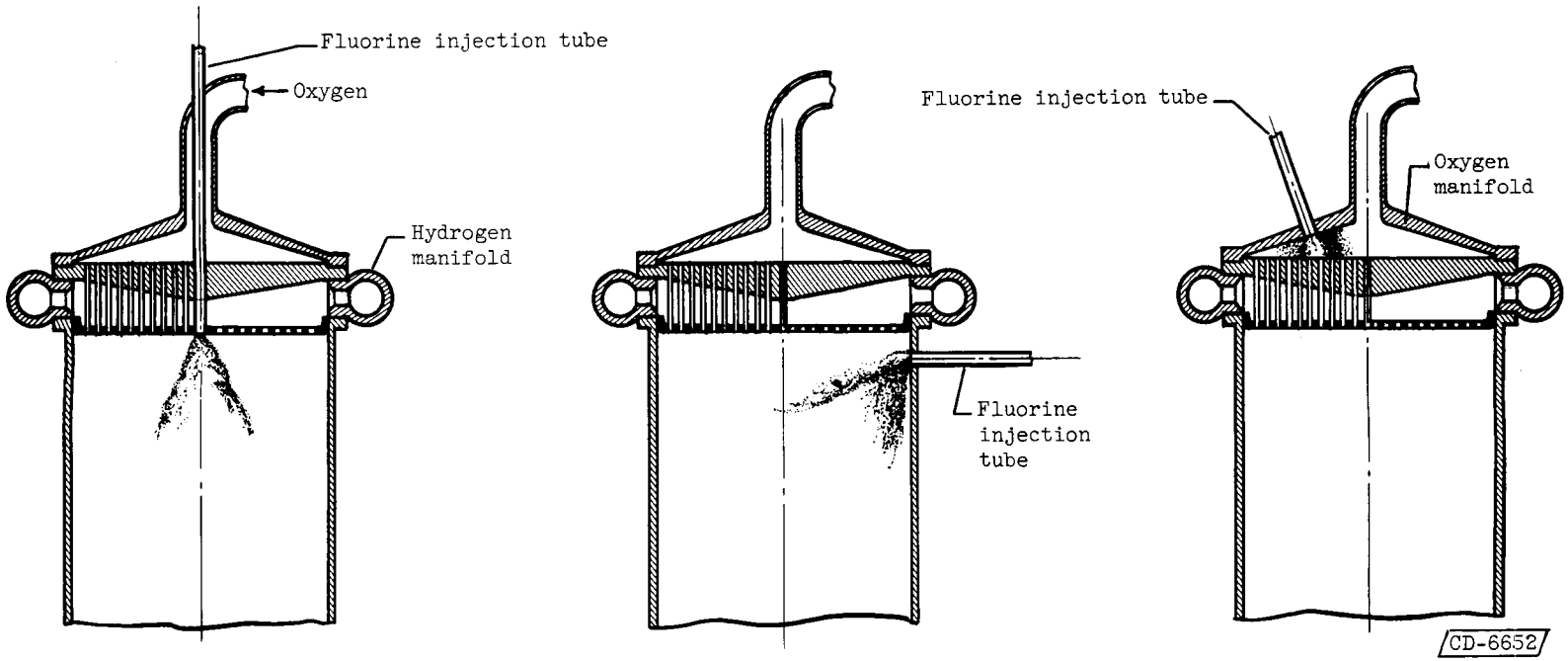

(a) Injector face injection.

(b) Side injection.

(c) Oxygen manifold injection.

Figure 6. - Fluorine injection points.

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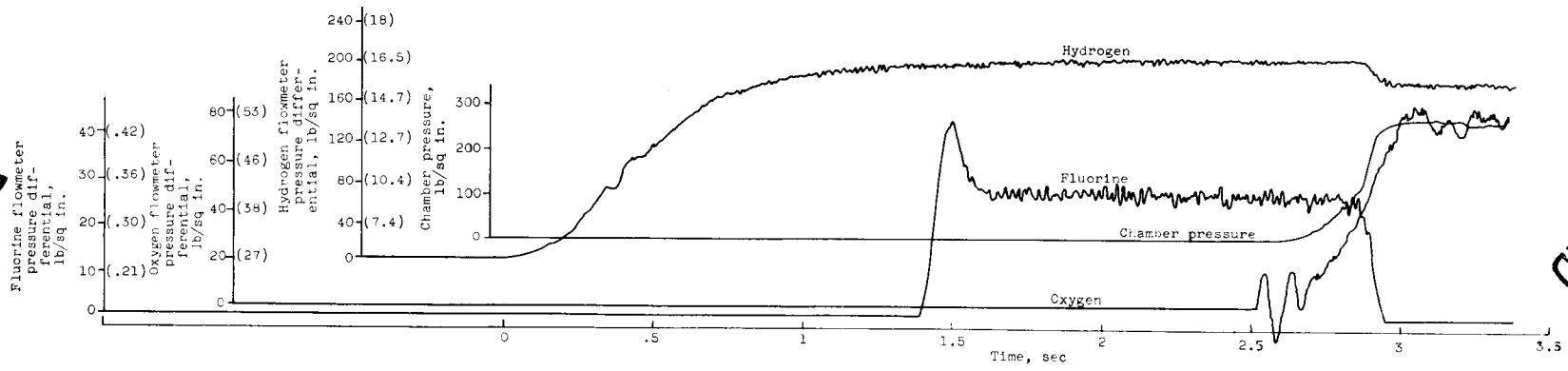

Figure 7. - Typical transient start data with fluorine ignition (run number 29). Numbers in parentheses are approximate flows expressed in pounds per second.

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(a) Back side of injector.

Figure 8. - Injector E after 22 engine starts with fluorine injection through oxygen manifold.

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(b) Front side of injector.

Figure 8. - Concluded. Injector E after 22 engine starts with fluorine injection through oxygen manifold.